

NASA TT F-9167

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FACILITY FORM 802	N 65 11309	
	(ACCESSION NUMBER)	(THRU)
	15 (PAGES)	1 (CODE)
	(NASA CR OR TMX OR AD NUMBER)	2 (CATEGORY)

Translation of "Études des Détonations Supersoniques".
 From 3ème Congrès International
 pour la Lutte Contre le Bruit,
 Paris, 13-15 May, 1964, pp. 1-6

OTS PRICE

XEROX	\$ 1.00 Ea
MICROFILM	\$ 0.50 mf

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
 WASHINGTON NOVEMBER 1964

A STUDY OF SUPERSONIC EXPLOSIONS

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"A Study of Supersonic Explosions" (Études des Détonations Supersoniques) by Pierre Lienard (Engineer, Doctor of Sciences, Head of the Acoustical Division of the National office of Aerospace Studies and Research, Member of the Noise Commission in the Ministry of Health), Office National d'Études et de Recherches Aéronautiques, Chatillon-Sous-Bogneaux, France.

The purpose of the study is to determine a method for predicting supersonic explosions and to calculate trajectories for which a given pressure amplitude will not be exceeded on the ground. A cathodic oscillograph, membrane pressure receivers, and mutual inductance receivers are used in the study. For uniform rectilinear flight the author concludes that it will soon be possible to calculate the excess-pressure on the ground under given conditions. It will also be possible to calculate the altitudes and velocities which would assure that an imposed limiting value for those excess pressures is not exceeded.

Hullas

1. General Phenomenon

The sonic phenomena which accompany supersonic flight are similar to those which have been observed for a long time by artillery men near their projectiles. However, in this case there is a change in scale

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Note: Numbers in the margin indicate pagination in the original foreign text.

with the moving body being very large and with the addition of energy resulting from accumulation of sound waves emitted by the moving body with a noisy propellor.

Therefore, a signal being observed is characterized both by a great intensity in the scale of acoustical levels and by a very extensive frequency spectrum. With passage of time, the pressure profile takes the shape of an N, which is well known (Figure 1a).

By way of an example, the excess pressure peaks which are reached by the steep fronts propagated around small projectiles are, according to our previous measurements:

- 8 mm rifle bullet, velocity $M = 2.2$, at 1m from the trajectory:
 $2,200 P_a = 22 \text{ mb}$;

- 8 mm rifle bullet, velocity $M = 2.2$, at 50 m from the trajectory:
 $110 P_a = 1.1 \text{ mb}$.

When a Mirage III B airplane, having velocity $M = 1.3$, reaches an altitude of 8,800 m, the excess pressure observed on the ground is
 $47 P_a = 0.47 \text{ mb}$.

When a Mirage IV airplane, having velocity $M = 1.6$, reaches 12,000 m in altitude, the calculated excess pressure would be $42 P_a = 0.42 \text{ mb}$.

These pressures are small with respect to the scales for the usual mechanical magnitudes (normal atmospheric pressure is 1 bar, or 100,000 P_a). The noises corresponding to sinusoidal pressures having these peak values would be at very high levels, but the auditory effect from one instantaneous excess pressure is fortunately nothing compared with that produced by these levels.

It can be left to competent physiologists to evaluate the inconvenience caused by these noises, but it is assumed that the excess pressure peak value is a characteristic quantity for this phenomenon. In performing work requested by the General Secretariat for Civil Aviation, O.N.E.R.A. collaborated with the Center for Flight Tests, the Technical Department of Aeronautical Aviation, the Franco-German Research Institute of Saint-Louis in order to measure the pressure profile obtained under different conditions of supersonic flight and to relate this to measurable characteristics of flight, the plane, the atmosphere, etc.

2. Some Ideas on the Theoretical Study

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The Theoretical study, which was initiated by the ballisticians, has been continued by several authors, and the foundations have been provided by the classic results of Whitham, for the case of rectilinear and uniform flight in homogeneous atmosphere, and by the results of RAO for the case of focalizations. This latter case occurs when, due to acceleration of the plane or to the atmospheric heterogeneity, different sonic regions envelope a caustic surface on which the transported energy is accumulated.

A mathematical study of excess pressure in the vicinity of a caustic surface has been studied at the Aerodynamic Division of the O.N.E.R.A., by J. P. Guiraud (Ref 1, 2). The importance and the complexity of these calculations do not allow me to even present a brief summary. We can

only indicate that the result of this is the excess pressure value produced on the ground following the impact of a ballistic wave, as a product of: the pressure calculated according to Whitham for the case of a simple ballistic wave without focalization, a coefficient which can be calculated numerically depending on the geometry of the plane, a coefficient depending on the Mach number of the plane and on its distance, and finally a universal function given the variation in the excess pressure along the caustic surface.

Very briefly, the maximum excess pressure on the ground, for the case of uniform rectilinear flight, increases with the Mach number M of the plane and decreases with the distance R from the ground to the trajectory (in practice, the altitude of the flight). In the case of focalization, the maximum excess pressure is a much more complicated expression, increasing with M and decreasing when the altitude of the plane increases, but also depending on the flight trajectory (curvature, acceleration) (see the Appendix, page 10).

3. Experimental Apparatus. Method of Study

An experimental study is therefore absolutely necessary in order to understand these phenomena, and the purpose of the studies undertaken here, as compared with theoretical studies, is to establish a method of determining supersonic explosions in advance, and consequently of determining trajectories which will make it possible to not exceed a given pressure amplitude on the ground.

By way of example, Figure 1a reproduces the recording of the pressure profile for an 8 mm bullet, obtained by an ONERA piezoelectric microphone. The recording of such signals requires that a frequency band of about 6 cycles to 80 kc be transmitted correctly. In the case of an airplane, due to the fact that long-distance propagation attenuates the shrill frequencies and extends the phenomena, the frequency band to be transmitted is much more limited toward the shrill frequencies, and in contrast must be extended toward the base frequencies up to about 1 cycle.

The briefness of the phenomenon makes it necessary that it be recorded (photographic, magnetic, or another way), which is the only way to examine it conveniently.

Photographic recording on a cathodic oscillograph makes it possible only to retain the form of the signal, but this apparatus is suitable for a laboratory for an exact study. However, the more common recording methods on the ground (magnetic or galvanometric) can, after an examination, provide useful information. In addition, direct photographic recording of an oscillogram does not make it possible to use several measurement channels, but an airplane flight is expensive, and it is therefore necessary to increase the observation points.

Due to the fact that the signal provided by a supersonic airplane at a high altitude has a frequency spectrum which is slightly extended toward shrill frequencies, it can be conveniently recorded by the magnetic frequency modulation process, with which one can arrange a great number of simultaneous measurement points.

Figure 1b shows the signal received on the ground from a supersonic

airplane at 10,000 m in altitude; the signal observed directly on the oscillograph, and that obtained by reading off the magnetic recording, are identical.

Figure 2 shows the general diagram for an installation on the ground: a microphone placed in front of the measurement microphone, with respect to the direction in which the airplane arrives, records a triggering signal. Each measurement channel is recorded on one of the tracks of the magnetic tape, and after the experiment the recordings are studied one by one in the laboratory.

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4. Selection and Arrangement of the Pressure Transducers

The important element in each measurement link is obviously the pressure transducer (or microphone).

The Center of Flight Tests utilizes membrane pressure receivers and mutual inductance receivers. The Research Institute of Saint-Louis utilizes Neumann capacitive microphones and ONERA piezoelectric receivers; the Technical Division of Aeronautical Navigation utilizes Bruel and Kjaer capacitive microphones.

The development of piezoelectric ceramics has led to the production at the ONERA of pressure receivers using barium titanate or lead zirconate discs which are very easy to use (Figure 3). These receivers and their measurement links are now produced commercially, and have been used for numerous pressure measurements on the walls of wind tunnels or shock tubes, or on mock-ups, rockets or airplanes.

The 20H42 receiver is in the form of a cylindrical unit made of

stainless steel which is 22 mm in diameter and 30 mm high, followed by a cable. The sensitive surface measures 1.75 cm^2 . The sensitivity is about 18 v/P_a ; the exact sensitivity is given by the calibration of each sample. The measurement extends from 2 to 10^5 P_a , and the frequency band transmits from 1 to 50,000 cycles with a suitable adapter ("cathode follower" having very large input impedance). This adapter is a cylinder 22 mm in diameter and 105 mm long located at the end of the cable coming from the receiver, at some tens of centimeters. The operational temperature is between -40 and $+90^\circ\text{C}$. The receiver endures humidity and rain and is not at all fragile. On the other hand, it is sensitive to vibrations, as well as to thermal radiation.

Studies are being carried out at the laboratory to improve the capacitive receivers and the adapters, which can make it possible to transmit very low frequencies (Ref. 3, 5). These links, which are more sensitive than piezoelectric receivers, can be used to record waves which have been subjected to a long propagation, and whose steep fronts are rounded off by the absorption of shrill frequencies. This is particularly true when it is necessary to record sonic phenomena at several points simultaneously. The arrangement of the microphones on the ground is of very great importance. In particular, every measurement apparatus disturbs the quantity which is being measured. In acoustics, if the apparatus is too large, the sonic diffraction modifies the pressure on the surface of the microphone. At times, it can be doubled when the ratio of the lateral dimensions of the microphone to the wavelength is too large, which leads to an error of 6 dB.

On the other hand, the ground reflects the sonic waves with a reflection coefficient which depends on the ground's properties and on the sonic wavelengths. If the sonic signal which is observed has a very extended frequency spectrum, this signal will be deformed by the presence of the microphone system and the ground. Therefore, the measurement will be wrong not only with respect to the scale of the phenomenon, but also with respect to the form itself with time.

In order to restore the true signal there are only two solutions: a very small microphone (small with respect to the smallest wavelengths of the sonic spectrum to be transmitted) located very far from the ground on a very thin support, or, on the contrary, a microphone set into a very large surface with respect to the longest wavelength, which reflects very well at all frequencies, so that the measured pressure is always exactly double the pressure propagated in unlimited air.

In the case with which we are concerned, a pressure transducer located a little bit above the ground yields very useful information, however. A more exact measurement is obtained by a microphone set into a metallic paving, which is itself set on solid ground, concrete, or packed earth.

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We have already indicated the possible disturbances which can have an influence on the receivers:

- as the vibrations in these experiments can be caused by excitation of the microphone stands by the shock waves, it is therefore necessary to avoid mountings on baffles which are too thin or mountings whose own frequencies occur in the pass band;

- the atmospheric infra-sounds are now received in the frequency band of the apparatus. It is impossible to avoid this, and this disturbance makes measurements made under high winds impossible;

- irregular solar radiation causes a disturbance of the same order, because the piezoelectric ceramics are sensitive to the thermal flux variations. This effect can be avoided with a suitable protection which stabilizes the thermal flux reaching the sensitive surface of the receiver: for example, a layer of silicon grease (a solution of the Saint-Louis institute) or a porous metallic plate (its use is being studied at ONERA).

5. Calibration

Since any measurement apparatus is only of interest if it is calibrated with sufficient accuracy, it is necessary to improve the calibration methods which are appropriate for the microphone characteristics mentioned above.

Since the latter have a very low sensitivity, an intense sonic field is therefore necessary so that they can give a usable signal. A powerful loud speaker makes it possible to make a good measurement of their response, but the latter has been supplemented by an analysis of impulse methods.

These methods themselves utilize sharp fronts (rifle bullet, shock tube) made up of simple signals, which are readily produced, for which the Fourier analysis is a very extended spectrum. These methods have been described in References 4 and 5, to which we refer.

6. Results and Conclusions

A great deal of information on shock waves has been brought together by the organizations cooperating in this study. The complexity of the phenomena still requires a great deal of work.

A theory is beginning to appear, whose results have been fairly well verified by experiments.

In the case of uniform rectilinear flight, it will soon be possible to calculate the probable excess pressure on the ground under given conditions, and, inversely, the altitudes and velocities which will assure that, for these excess pressures, an imposed limiting value is not exceeded.

The different causes of focalization which lead to local amplification of the former phenomenon are too difficult to be studied. The points on the ground where they occur cannot be determined in advance with any accuracy. Their measurement will necessitate, therefore, a very large number of measurement points distributed over a vast open surface, by means of special experiments, making recordings of the "super-bangs" caused by the evolutions of a test plane.

These studies have been undertaken, and they will be continued until it is known how to determine a trajectory for supersonic airplanes which will make it possible to forget about them.

Appendix

Summary Results of the Theoretical Studies

In uniform rectilinear flight, the airplane causes an excess

pressure on the ground, whose maximum is ΔP_4 :

(Whitham)

$$\frac{\Delta P_4}{P_0} = r_1^{1/2} (r_1^2 - 1)^{-1/2} \left(K_v v + K_p \frac{P \ell}{P_0 v^2} \right)^{1/2} \ell^{-1/2} L^{-1/2}$$

V_0 = velocity of the airplane, M = Mach number,

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v, p, ℓ = volume, weight, and length of the plane,

K_v, K_p = coefficients of volume and lift depending on the airplane,

L = distance of the airplane from the observation point,

P_0, ρ_0 = pressure and density of air on the ground.

If a caustic is produced, the excess pressure on the caustic is approximately:

(Guiraud)

$$\frac{\Delta P_c}{P_0} = \left(\frac{L}{R} \right)^{1/2} \left(\frac{\Delta P_4}{P_0} \right)^{1/2}$$

as a function of the former excess pressure ΔP_4 obtained beyond the caustic, the curvature region R of the latter, and the distance L from the airplane to the caustic.

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Studies of Supersonic Explosions

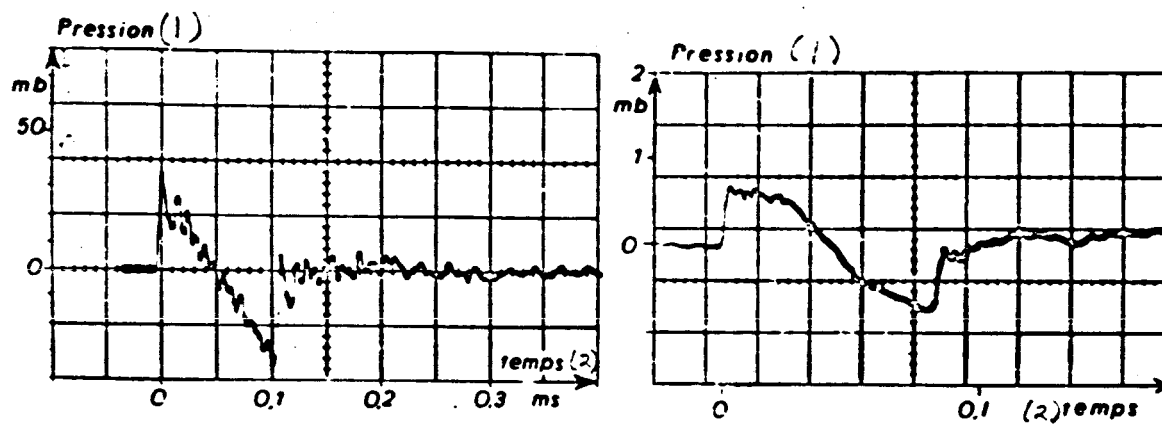


Figure 1. Pressure Recordings of a Ballistic Wave

a). Rifle Bullet, $M = 2.2$, at
one meter from the trajec-
tory
(1) pressure; (2) time

b). Mirage III B airplane,
 $M = 1.4$, altitude 7,000 m.
(1) pressure; (2) time

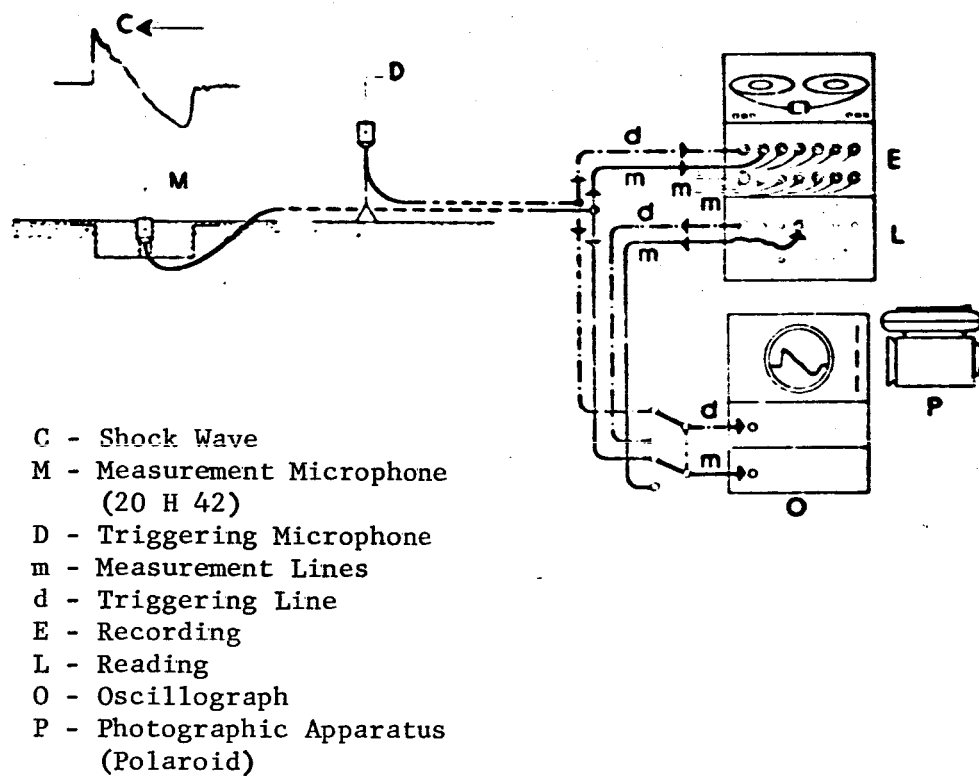


Figure 2. Diagram of the Recording Apparatus
for Supersonic Explosions

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